An Open Web-Based Repository for Capturing Manufacturing Process Information

Conference Paper · August 2016

DOI: 10.1115/DETC2016-59265

Proceedings of the ASME 2016 International Design Engineering Technical Conferences and
Computers and Information in Engineering Conference
IDETC/CIE 2016
August 21-24, 2016, Charlotte, North Carolina

DETC2016-59265

AN OPEN WEB-BASED REPOSITORY FOR CAPTURING MANUFACTURING PROCESS INFORMATION

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ABSTRACT

With recent progress in developing more effective models for representing manufacturing processes, this paper presents an approach towards an open web-based repository for storing manufacturing process information. The repository is envisioned to include several new use cases in the context of information use in smart manufacturing. This paper examines several key benefits through usage scenarios engaging existing engineering activities. Based on the scenarios, the desired characteristics of an open web-based repository are presented, namely that it will be (1) complementary to existing practices, (2) open and net-centric, (3) able to enforce model consistency, (4) modular (5) extensible, and (5) able to govern contributions. A repository will support and motivate the ubiquitous and extended use of standardized representations of unit manufacturing processes in order to promote consistency of performance assessments across industries and provide a tangible, data-driven perspective for analysis-related activities. Furthermore, the paper presents additional benefits and possible applications that could result from a shared manufacturing repository.

NOMENCLATURE

LCA Life Cycle Assessment
LCI Life Cycle Inventory
UMP Unit Manufacturing Process
XML eXtensible Markup Language

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1 INTRODUCTION

Smart manufacturing is quickly changing the way in which organizations design, control, and maintain their product and production systems. The combination of web-based tools, onboard sensing technology, and wireless communication, together present new manufacturing-related business cases that have not been realized before. This emerging field requires additional support, e.g., in the form of formal methods, frameworks and standards, to fully take advantage of the affordances provided by the complete suite of new technology.

Recently, the ASTM International E60.13 subcommittee on sustainable manufacturing has focused on a standard to formally characterize manufacturing processes to enable the seamless sharing and use of structured manufacturing information [1]. Implementing this standard will contribute to improving manufacturing practices, including optimizing process plans, minimizing energy consumption, and better controlling material flow through an entire production scenario. The broad dissemination of this approach will present a number of additional advantages. In other words, when a group of manufacturers adopt compatible modeling methods and share information across organizations, opportunities for system-wide analysis that were not available before become possible.

These opportunities motivate the design, development, and deployment of an open repository for organizations to share and subsequently procure manufacturing information. Such a repository will provide an environment in which industry, academia, and government agencies can share non-proprietary process-specific information, access appropriate models, and reuse manufacturing information.

A challenge for this effort will be the fact that traditional manufacturing systems lack unifying frameworks to enable seamless sharing and reproducibility of manufacturing-related data [2]. For example, a stamping process to produce a door siding for an automobile has significantly different requirements than a similar stamping process for a bottom plate of a stapler. As a result, it is critical to define a format and the necessary data to be shared between manufacturing processes and systems models to ease information reuse and retain its fidelity.

Since the proposed repository will be populated by a network of manufacturers, it is critical to understand the issues with deploying a distributed, shared ecosystem, including validation procedures for entries, incentivization models to promote participation, as well as issues related to knowledge and data representation. Additionally, the development of a repository for manufacturing process information will influence the protocol for characterizing manufacturing processes. As new manufacturing processes are introduced, the repository will provide a baseline for assessing the new manufacturing capabilities. This will be particularly impactful for smaller, individual manufacturers, as this repository would provide a way of quantifying their own performance (e.g., in the context of sustainability, productivity, efficiency) and distinguish them from their competitors.

This paper is structured as follows. Section 2 first presents an overview of work related to the development of a generalized representation form for unit manufacturing processes (UMP). Then, Section 3 presents new directions towards an open UMP repository. The objective for the repository will be to aid operational decision making for small and medium-sized manufacturers. Large manufacturers may also use the repository as a model for their own work. Section 4 then focuses on the benefits as well as applications of such a repository in the context of specific scenarios. Finally, Section 5 presents a set of requirements (or characteristics) for the development of the repository and its architecture, followed by the broad implications of this effort. Section 6 concludes the paper.

2 BACKGROUND AND RELATED WORK

Unit manufacturing processes are defined as the individual steps of a manufacturing system that involve the controlled application of energy, to convert raw materials into finished products with defined shape, structure, and property [3]. One of the key goals of modeling UMPs is to enable advanced analysis, e.g., determining energy consumption of a production process chain, evaluating the sustainability performance of a process, and comparing performance across different processes [4]. Throughout this paper, the context of sustainability is used as a case study to help later generalize this modeling approach to manufacturing analysis as a whole.

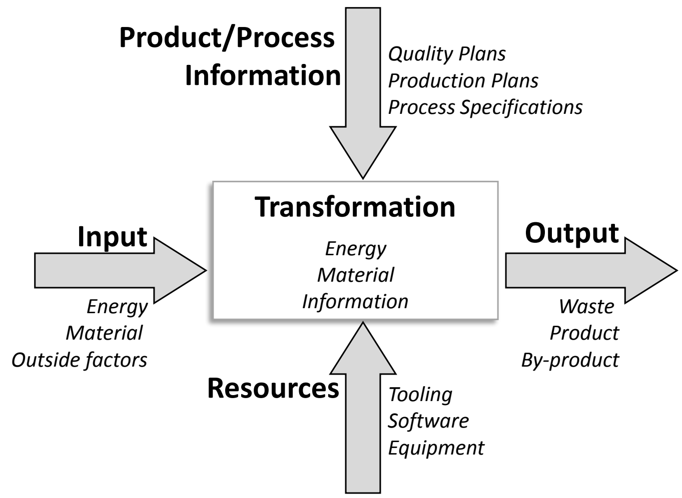

FIGURE 1. Abstract depiction of single unit manufacturing process. The proposed data representation of a UMP includes inputs, process-specific information, and resources that instantiate defined transformations to produce information regarding process-specific outputs.

In 2015, ASTM E2986-15, the *Standard Guide for Evaluation of Environmental Aspects of Sustainability of Manufacturing Processes*, was passed [1]. This standard marked the ATMS's first sustainable manufacturing standard and focuses on sustainability improvement for a single production process. The steps outlined in ASTM E2986-15 support the data collection needed for the formal characterization of manufacturing processes as well as the use of relevant analysis techniques. In 2016, the companion standard, ASTM E3012-16, the *Guide for Sustainability Characterization of Manufacturing Processes*, was passed [5]. The focus of ASTM E3012-16 is on standardizing a formal representation of manufacturing processes such that they can be parameterized and reused. Collectively, the two standards provide guidelines for procuring necessary data from a manufacturing asset and for building its UMP model. Figure 1 presents a depiction of how UMPs are modeled according to ASTM E3012-16. The UMP is composed of five information flows:

Inputs: material/energy flows into the manufacturing process.
Product/Process Information: all control parameters associated with process and production planning.
Resources: tooling and equipment needed to complete process.
Transformation: rules, equations, and associated uncertainty relating inputs and control parameters with the outputs.
Outputs: all associated products and waste.

The remainder of this section presents existing efforts related to (1) formally characterizing manufacturing processes for engineering activities and (2) developing community-based repositories for sharing manufacturing information.

2.1 Formally characterizing manufacturing processes for engineering activities

The formal characterization of manufacturing models provides a number of benefits for decision makers. One of the most common approaches is modeling the production system as feedback control loops with the goal of optimizing production and floor plans [6]. At the machine level, or the unit model, modeling using a formal data representation has allowed researchers to conduct more detailed and accurate environmental analyses of manufacturing activities [7]. This method has been shown to be appropriate across a number of different process technologies, including metal grinding [8], injection molding [9, 10], die casting [11] and laser cutting [12]. These studies have demonstrated the effectiveness of formally characterizing manufacturing processes. However, if two of these studies are closely examined, e.g., Li et al. (2012) [8] and Kellens et al. (2012) [12], it is apparent that the modeling techniques of individual UMPs are complementary to one another but not compatible.

In response, recent work has extended these efforts by moving towards a unified schema of process models. One of the primary contexts of these efforts is within life cycle inventory (LCI) database development, so that life cycle assessment (LCA) practitioners can conduct more streamlined environmental analyses [13]. The goal is to enable parametric analysis, wherein practitioners can adjust input variables to match their systems, study the variability in the resultant predictions, and benchmark their own processes against best practices. This perspective has enabled new research areas, such as web-based simulation [14], energy estimation tools from process plans [15], and ontology development for LCA-related data [16]. However, to fully realize the benefits of these approaches, the community requires a standard for representing UMP models, which could lead to a distributed sharable repository of manufacturing information.

2.2 Developing community-based repositories for sharing manufacturing information

Since no central repository of available manufacturing resources exists, often optimization opportunities for assessing production scenarios are lost and not explored [17]. This is an example of an issue with greater impact. Lacking a standardized protocol for capturing, storing, and revisiting manufacturing information, redundancies in organizations, or more broadly across industries, are inevitable. That being said, there have been efforts in capturing both manufacturing data and knowledge for specified purposes. The unit process life cycle inventory (UPLCI) framework within the CO2PE! Initiative was developed to store manufacturing specific LCI information for environmental analysis [12]. Additionally, the National Renewable Energy Laboratory (NREL) provides an LCI database for US-specific manufacturing processes [18, 19]. This database is designed to interface directly with existing LCA software and conforms to the Ecospold format [20]. CES EdupackTM provides a material database with accompanying manufacturing data to aid material selection during product development [21].

Though these databases or repositories enable specific engineering activities based on their design intentions, they lack rigorous description of the manufacturing process itself and incorporate far too liberal assumptions. For example, using LCA databases, the environmental impact of manufacturing processes is scaled by the weight of the part produced. Information regarding specific resources (tool, cutting fluid, etc) is not reflected as part of the description of the unit process. Instead, these considerations are presented as separate material flows. To better describe manufacturing processes and the surrounding material and energy flows, the ASTM standard defines an XML-based schema for formally characterizing UMPs [5]. This standardized format will enable consistent and broad contributions to a centralized repository of UMPs.

3 Open Repository for Unit Manufacturing Processes

Figure 2 presents a broad vision of the repository. The UMP repository will house detailed models that characterize different instances of manufacturing processes and will interface with web-based applications to aid engineering activities for small and medium-sized enterprises. As shown in the figure, supporting interfaces can be categorized into two broad categories: domain-specific activities and general tools. Supported domain-specific practices will include life cycle inventory (LCI) analysis, process monitoring, and process design and planning. Such domain-specific applications will then interface with a set of general tools, including an optimization toolbox that will house useful algorithms, a simulation suite to enable interoperability with commercial tools, and a visualization toolbox for the mapping of visual variables to manufacturing-related data. The modeling technique specified in the ASTM standard is designed to capture activities across the manufacturing landscape while remaining complementary to traditional engineering practices, such as process plan optimization and life cycle assessment. The standard defines an abstract format for modeling which will be specialized for different processes and/or families of processes. Approaches to specialization is an area of on-going research.

To support different computing platforms (e.g., tablets and traditional desktop computers), the repository will be web-based and populated by manufacturing model contributors. The structure of the repository will be supported by an accepted manufacturing or material taxonomy, e.g., Allen and Todd manufacturing taxonomy [22]. A well-structured repository will enable the reuse of stored information, including querying mechanisms and similarity assessment. A web-based repository can take advantage of existing open-source libraries, and tools for add-on features, such as information visualization, advanced querying, and distributed data storage.

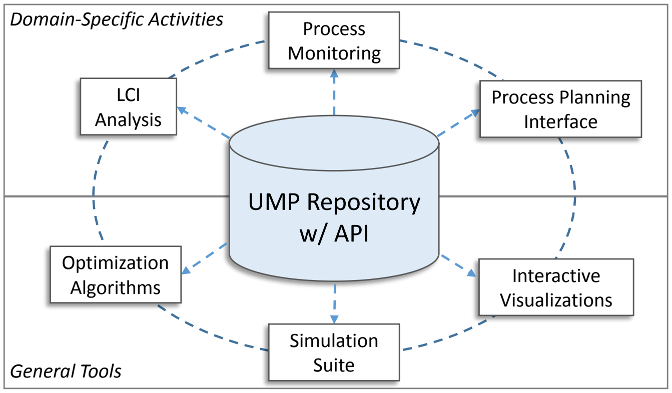

FIGURE 2. Depiction of the multiple uses of the UMP repository. The repository will be designed to interface with general tools, including optimization algorithms, a simulation suite, and an interactive visualization toolbox, that can be leveraged within domain-specific activities, such as LCI analysis, process monitoring, or process planning.

4 USAGE SCENARIOS

This section examines three scenarios for the use of the repository: (1) information exploration and communication, (2) life cycle assessment, and (3) simulation methods for decision support. The sections below specify how the repository would contribute to each of these cases.

4.1 Information Exploration and Communication

Manufacturing processes are numerous and their variability great. The ability of a user to understand the structure and coverage of the database and then to find the appropriate model will be fundamental to the repository's success.

Given that the repository will house a significantly high volume of manufacturing process information, the exploration and basic communication of the data will be of paramount importance [23]. Developing a broad perspective of what is included in the repository and the relationships between UMPs will require well-defined interactions. Applying interactive visualization and visual analytics-based techniques help alleviate challenges related to information exploration [24]. In other words, mapping appropriate visual variables to the attributes of manufacturing processes will enhance the usability of the repository. Stakeholders will be able to use the visualization-based interfaces to explore the repository and discover non-obvious relationships between UMPs, including assessing the compatibility of resources amongst several processes and understanding the similarities of a set of processes. This thinking could lead to additional research thrusts to incorporate visualization-driven queries for the engineering or manufacturing-specific domain. Through the implementation of visual analytics-based approaches, applications that interface with the repository will provide insight into the material and manufacturing selection process during the product design phase, by exposing non-obvious relationships.

A fundamental purpose of the ASTM standard for UMP modeling and the associated XML presentation is for consistent communication of the manufacturing processes including their inputs, outputs, and the flows between them. For example, if a company wishes to present a portfolio of their manufacturing capabilities, by basing the representation of their processes on the ASTM standard format, tools can be developed to provide visualizations with structured data suitable to their domain. A common format for representing manufacturing processes and a central repository that houses them will also create new streamlined avenues for information communication and business opportunities. Stakeholders at multiple levels in the enterprise will be able to quickly access data about specific manufacturing processes, including information regarding needed resources, material requirements, and process efficiency.

Furthermore, the repository will serve as a collaborative mechanism and achieve more streamlined inter-organizational information flow. Madenas et al. recently pointed out that such methods are lacking [25]. When fully realized, the repository will contribute to enhanced transparency across organizations' supply chains, to enable more precise simulation models, product life cycle considerations, and, more generally, decision support. For example, if a designer wishes to explore all material and energy input requirements for a specific process, that information would be easily obtained and delivered in a standard format to compare against other processes.

4.2 Life Cycle Assessment

To conduct a Life Cycle Assessment (LCA), practitioners must collect all related manufacturing information for the given product, process, or system [13]. The LCA community relies on databases containing aggregated information about basic unit processes, such as the environmental impacts associated with consuming 1 kWh of electricity from the US grid. Entries that model manufacturing processes carry significant uncertainty and rarely translate directly to real-world production scenarios. A detailed repository containing process models will help LCA practitioners improve the accuracy and rigor of their analyses.

One of the most widely agreed upon challenges for LCA practitioners is the availability of readily usable data to populate and update life cycle inventory databases [26]. Even when machine data is available, it is often infeasible to directly include processing information into an LCA without the assistance of LCA experts. This is particularly a challenge for small and medium-sized enterprises.

ASTM 3012-16 is meant to provide a complementary format to be compatible with existing LCA frameworks and methods. Currently, unit processes as defined by the ISO 14000 series include the inputs and outputs associated with a specific process. This modeling paradigm does not include all available control parameters and resources; it only takes into account the unit amount of inputs (e.g., degradation of tool used, electricity, and material) and outputs (e.g., product, by-product, and emissions). In other words, optimizing environmental performance for a process plan, based on existing available information, does not exhaustively search all feasible solutions but only finds an average case solution. Similarly, conducting an LCA without a robust repository of manufacturing processes can introduce significant uncertainty. As a result, sources of significant uncertainties, including the sparseness of LCA databases, have now become a grand challenge in the LCA community.

Internally, some organizations have developed parametric LCA models to streamline revisions and additions to existing life cycle inventories that characterize their processes. These efforts typically focus on specific categories of products or company-specific unit processes. From this perspective, the UMP repository will serve as an enabler for the broad realization of parametric LCA. Ultimately, the UMP repository could provide up-to-date information, including region-specific data, leading to more precise and time-relevant analyses. Additionally, multiple design comparisons and advanced life cycle simulations could be achieved more easily in a streamlined manner by leveraging the power of crowd-sourced information. This could fundamentally change how LCAs are conducted [27]. This idea is further explained in the following section.

4.3 Simulation for decision support

Sustainability analysis in manufacturing is a multi-criteria decision problem [28, 29]. Evaluation of the different manufacturing process alternatives is fundamental to making optimal decisions. Current industry practices to compute and compare sustainability of manufacturing processes are inconsistent because of a lack of uniform methods to represent manufacturing processes and equipment performance. Thus, sustainability analysis offers one example for the eventual use of the repository.

The repository will enforce a common structure and procedure for identifying and capturing key information needs to assess manufacturing performance. This will enable designers to link individual UMP information models together to create a network or system of UMP models that will extend the characterization of environmental aspects beyond an individual process to a production system or the product. In other words, the repository will support interfaces with a plug-and-play approach to represent the actual flow of material, energy, and information between manufacturing systems within a manufacturer's unique environment. UMPs provide the building blocks from which virtual representations of manufacturing systems can be put together, shared, and reused within simulation environments for evaluation of the trade-offs.

In general, the repository will be valuable when used in conjunction with other environmental assessment and simulation tools for decision support. Since manufacturing information on process inputs and resources will be generically stored to enable transformation into the desired output, results can be application specific. For example, the repository will support discrete event simulation (DES) tools to calculate and assess energy consumption and material usage [30]; it will also contribute to system dynamics models to represent transformations [31]. As a result, material and other resources can be aggregated downstream in the product lifecycle and hotspots or bottlenecks can be identified, analyzed, and mitigated.

Beyond sustainability considerations, the UMP repository will also serve as a tool for general production analyses, including contributing to the simulation of virtual factories [32], integration of distributed simulation tools [33], as well as prognostics and health management considerations [34]. Figure 2 presents this vision of compatible and interoperable suites and tools that will curate manufacturing information from the UMP repository. Each suite will present unique functionality that together will support additional use cases. Based on the above usage scenarios and the broader vision, the desired characteristics (or a set of requirements) for the UMP repository are presented in the next section.

5 DESIRED CHARACTERISTICS

This section presents the target characteristics that will guide the implementation of the UMP repository. Though this is not an exhaustive list of desired attributes, it presents the critical components to meet the needs of the usage scenarios discussed above in Section 4.

5.1 Complements existing practices

Attributes of a composable UMP model must be compatible with existing engineering practice including advanced simulation and accompanying analyses. To address this need, the UMP repository needs to complement activities, such as LCA, production floor monitoring, and decision making processes. The ASTM standard was developed to be consistent with LCI analysis. Since sustainability goals must always be balanced with other corporate objectives, it is also critical to capture appropriate data to assess those other goals, such as productivity, efficiency, and cost.

5.2 Open and net-centric

Housing a broad range and significant volume of manufacturing information presents a number of opportunities for the engineering community. Existing Web 2.0 technologies, e.g., D3.js and MongoDB, help support seamless, user-guided exploration of data [35]. In the context of manufacturing processes, these technologies can be employed to realize emergent relationships within the data. For example, storing metadata associated with each UMP will enable the introduction of intelligent algorithms for type-matching, clustering, and user-guided querying. This supports hypothesizing non-obvious what-if scenarios, including comparisons across multiple manufacturing processes as well as entire supply chain networks.

The repository will be built using Web 2.0 technologies. This includes releasing the application program interface (API) so that others can contribute to the extension of the repository and develop applications for specific engineering-related activities, e.g., production simulations, trade space exploration, and life cycle assessment.

5.3 Enforces model consistency

With an open community, it is critical to retain a consistent data representation across different entries [36]. To address this need, the template for entity structure will abide by ASTM E3012-16. This requirement also refers to the ability to properly handle the removal of entities. For example, it is critical to remove linked data associated with a deleted entity to avoid conflicts with user queries. We will impose a strict schema as a template for contributors to limit issues related to conformance and consistency. It should be noted that the template for the data representation must also allow for interoperability across the included software.

5.4 Modular

The repository will be developed in a modular fashion so that the core functionality of storing UMPs will not affect external interfaces, such as simulation interface, data visualization interface, and the process plan composability interface. This will aid in the overall development of the repository, since efforts can be distributed across the various components in parallel. The function of how entities are stored within the repository correlates with its actual use. For example, experts in the area of polymers should be able to filter down to their specific core areas within the repository.

Figure 3 illustrates some possible roles of users and demonstrates the use of modular domain-specific interfaces that will extract data from the repository. Process engineers might want machine or process-specific information to set parameters and controls for a single process. To conduct a life cycle inventory analyses, an environmental manager would be interested in the inputs and outputs of multiple UMPs. Design engineers will be able to explore multiple process plans or line managers could monitor performance of a production line based on thresholds. We envision the repository to enable such workflows independent from one another.

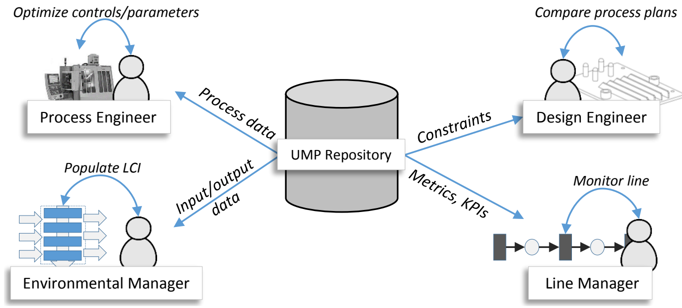

FIGURE 3. Illustration of possible uses of the repository. We consider four hypothetical users each representing unique roles accessing task-specific information from the repository. We envision that each stakeholder would access target data through specialized interfaces (see Figure 2). For example, to optimize the controls and parameters of a specific machine, a process engineer would extract process-specific data and use an optimization interface to set machine parameters.

5.5 Extensible

The repository will have the necessary architecture to allow the ability to extend and append models. This could include the ability to edit an existing UMP and its metadata, extend the capability of existing manufacturing processes, or append the repository with new UMPs.

Beyond the core capability of dealing with data expansion, it is also necessary to develop appropriate vetting procedures for new entities. This vetting protocol must be from both the perspective of (1) the stakeholder (or origin) of the submitted information and (2) the consistency and conformance of the data entity itself. Properly defining requirements for the appropriate structure of data entities for the contributors has a significant effect on the quality of crowd-based contributions. This is of critical importance, since manufacturing information accepted into the repository needs to be accurate and up-to-date.

5.6 Governs contributions

A variety of process models will be submitted to the repository, where each will exhibit different levels of granularity, specificity, and accuracy. As a result, the architecture of the repository must allow for the appropriate governance of the repository contents to support validation procedures, allowing (1) manufacturers to contribute their own process models and (2) stakeholders to vet and curate information. The governance model will set policies whereby UMPs can be properly validated.

6 CONCLUSION AND FUTURE DIRECTIONS

The main goal of the repository is to support existing engineering activities with a common home for manufacturing process information. We envision that contributors to this effort will develop compatible suites and interfaces that present value to a specific domain. These may include information visualization, process optimization, factory simulation, performance simulation and lifecycle inventory analysis. In order to fully realize its potential, this effort requires significant external participation from various stakeholders, including universities, government agencies, and industry partners. Participation includes populating the repository and developing compatible tools and suites to add value to the project. Since the development of the repository and its accompanying interfaces will require a distributed network of participants, vetting procedures for information and support must be formalized.

This paper presented usage scenarios and a set of desired characteristics for a repository of unit manufacturing processes. The repository will follow the ASTM International guidelines for formally characterizing unit manufacturing processes. Possible usage scenarios were presented in Section 4 and the desired characteristics or requirements of the repository to meet these usage scenarios were presented in Section 5.

Future directions include conducting case studies that properly demonstrate the features mentioned throughout this paper.

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